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Field-based crop phenotyping: Multispectral aerial imaging for evaluation of winter wheat emergence and spring stand

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ABSTRACT

The physical growing environment of winter wheat can critically be affected by micro-climatic and seasonal changes in a given agroclimatic zone. Therefore, winter wheat breeding efforts across the globe focus heavily on emergence and winter survival, as these traits must first be accomplished before yield potential can be evaluated. In this study, multispectral imaging using unmanned aerial vehicle was investigated for evaluation of seedling emergence and spring stand (an estimate of winter survival) of three winter wheat market classes in Washington State. The studied market classes were soft white club, hard red, and soft white winter wheat varieties. Strong correlation between the ground-truth and aerial image-based emergence (Pearson correlation coefficient, $r = 0.87$) and spring stand ($r = 0.86$) estimates was established. Overall, aerial sensing technique can be a useful tool to evaluate emergence and spring stand phenotypic traits. Also, the image database can serve as a virtual record during winter wheat variety development and may be used to evaluate the variety performance over the study years.

1. Introduction

The United States is one of the largest wheat producing country in the world (Carver, 2009). Within the U.S., Washington State produces both winter and spring wheat in various market classes such as hard red and white, soft white, and club wheat, with a production value of up to $1.18 billion annually. About 80–90% of the wheat produced in Washington is exported to countries such as Japan, Philippines, Taiwan, South Korea and Yemen (Washington Wheat Commission, 2008). Although growers produce both spring and winter wheat varieties in different market classes, approximately 75% of the wheat is planted as winter wheat, and 60% is planted as soft white winter wheat (Washington Wheat Commission, 2008). Winter wheat is the preferred wheat market class because they are high yielding (3.8 MT/ha in comparison to 2.8 MT/ha for spring wheat) and require low farm inputs. Moreover, winter wheat plants establish a soil cover to reduce wind and water erosion during the winter months (Carver, 2009).

The specific physiological changes unique to winter wheat are acclimation and vernalization that occur during cold winter months. Cold acclimation allows the plants to survive the winter and vernalization induces reproductive growth, which triggers flowering the following summer (Skinner, 2009; Snape et al., 2001). Vernalization requires growth periods in temperatures less than 4 °C, whereas freeze–thaw cycles leading up to cold winter months enhances cold tolerance in wheat (Skinner and Bellinger, 2010). If the winter hardiness of a plant variety is not sufficient to withstand extremely low temperatures (−16 °C or lower), the plants will die. Similarly, if the vernalization is not met completely, it may delay plant maturity due to delayed reproductive growth (Yan, 2009). Different winter wheat varieties will differ in the period needed for vernalization and winter hardiness. Therefore, these factors are critical phenotypic traits that need to be evaluated during new winter wheat variety development.

In Washington State, various agroclimatic zones provide variation in the physical growing environment of winter wheat, and thus the traits needed to maintain high yield potential. In the east-central part of Washington, wheat is grown under annual rainfall, which is typically limited to less than 30.5 cm annually (Hasslen and McCall, 1995; Higginbotham et al., 2011, 2013; Martínez et al., 2013). As such, a fallow year is incorporated into the rotation to try and store moisture to maximize crop production (Juergens et al., 2004; Higginbotham et al., 2013). After considerably dry years, wheat must be planted 15–20 cm deep in order to reach moisture and emerge (Schillinger et al., 1998; Schillinger

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and Paulitz, 2014; Young et al., 2014). During the germination stage, the seedling root and coleoptile (leaf-like structure that protects the first leaf from the soil) develop. Several factors including soil and air temperature, water availability, oxygen, radiation intensity, substrate, maturity of the seeds, and physiological age of the seed affects the germination of winter wheat (Lindstrom et al., 1976; Winter et al., 1988; Giri and Schillinger, 2003). A limitation to emergence can be rain events. If rain occurs before plant emergence, a solid crust forms on the soil surface which further impedes the emergence of wheat seedlings (Schillinger et al., 1998; Young et al., 2014). After successful emergence, plants must then survive the cold winter months. This typically occurs as plants acclimate to the weather and go into dormancy, with a layer of snow cover protecting them from the coldest of months (Skinner, 2009; Young et al., 2014). In years of extremely low temperatures or no snow cover, wheat seedlings become very susceptible to winter kill. Thus, two very important traits for wheat cultivars grown in the east-central regions of Washington are the ability to emerge from deep planting through crust events, and winter survival.

Researchers have reported proximal and remote sensing applications using ground and aerial platforms for vegetation dynamics such as leaf area index in different scales (Gitelson, 2004; Zhang et al., 2003; Lelong et al., 2008; Hunt et al., 2010, 2013; Fiorani et al., 2012; Sharabian et al., 2013; Deery et al., 2014). The platforms can range from field tractors, unmanned aerial vehicles (UAVs), or satellites. Although the satellite images can cover a large area, frequency of data collection, legal spatial resolution, and environmental factors including cloud cover can limit image-based crop evaluation (Zhang and Kovacs, 2012). Similarly, ground platforms can be limited by field conditions (especially after irrigation or rainfall) and coverage area at a given time. Such limitations can potentially be addressed by rapidly evolving UAV technology. Low cost UAVs may allow rapid need-based high resolution imaging critical for field phenotyping as number of trials and size of field plots are smaller in such applications. Some of the technological limitations of the UAV platforms for agricultural imaging include limited flight time (associated with battery life), and payload carrying capabilities (Hardin and Hardin, 2010; Zhang and Kovacs, 2012).

Digital images can be used for detecting early plant vigor. Recently, 50 winter wheat cultivars were monitored for two years to establish the relationship between early plant vigor index (EPVI was defined as the ratio between the difference of reflectance at 750 and 670 nm, with that of reflectance at 862 nm) and relative amount of green pixels, and a relationship with a regression coefficient of 0.98 was found (Kipp et al., 2014). Although strong relationships have been found to estimate plant vigor, the utilization for field evaluation during plant breeding is relatively new, and not used as a standard method. Therefore, the objective of this study was to evaluate the potential of low altitude remote sensing technology as a high-throughput phenotyping tool for assessment of winter wheat emergence (vigor) and winter survival (winter hardiness) under field conditions.

2. Materials and methods

2.1. Field plots

Winter wheat plots were planted into a summer fallow field in Kahlotus, WA on 23rd August, 2013. Plots planted were soft white and hard red winter wheat varieties from the Washington State University (WSU) Wheat Breeding Program, and soft white club wheat varieties from the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Wheat Breeding Program. Plots were planted in an alpha-lattice design using a custom built deep-furrow small plot planter consisting of 4 rows. Alpha-lattice design method divides replicates into incomplete blocks that contain a part of the total number of entries (Patterson and Williams, 1976). Alpha-lattice designs have been shown to be more efficient at analyzing data in large entry plant breeding trials when compared to randomized complete block designs (Yau, 1997). In this study, genotypes were distributed among the blocks in such a way so that all pairs occur in the same block at equal frequencies, thereby permitting removal of incomplete block effects from the plot residuals (Patterson et al., 1978).

The seeds were placed at 9 cm soil depth, and plot size was 1.5 m $\times$ 4.6 m. Each variety was replicated three times, except the club wheat trial that had one to two replicates (Fig. 1). The soil type in Kahlotus is a Ritzville silt loam. Currently grown cultivars in each market class (soft white, hard red, and soft white club) were planted as check cultivars (reference plots), and the remaining plots were experimental breeding lines from the two wheat breeding programs. Base fertilizer in the field was 27.2 kg of N, and all other standard field practices were performed by the cooperating grower.

On 25th August, 5.6 mm of rain was recorded followed by high daytime temperatures, which created a solid crust on the soil surface approximately 5 mm thick. The first plants were observed to emerge from the soil on 30th August. Emergence continued for another ten days. On 25th September, plots were rated visually for emergence. Each plot (1.5 m $\times$ 4.6 m area) was scored on a scale of 0–100% emergence using 10% increments. Plots were again rated visually on 9th April, 2014 to determine winter survival (spring stand).

2.2. Aerial data collection

An unmanned aerial vehicle was used to acquire high resolution multispectral images to evaluate the winter wheat emergence (2nd October, 2013) and winter survival (16th April, 2013). The UAV (HiSystems GmbH, Moormerland, Germany) system weighs about 2 kg without the imaging system and a 6000 mA h Lithium Ion Polymer battery that provides the required power for UAV flight. The flight time can range from 10 to 20 min depending on the payload and wind conditions. The maximum recommended payload of this system is 2.5 kg. The UAV has eight brushless motors and individual motors can handle 20 A power with a maximum thrust of 2200 g. Based on preliminary flights, beechwood propellers (Xoar International, CA, USA) were found to improve the stability of the UAV platform during imaging and were used in this study. The UAV comprises of an array of onboard sensors for flight stability and waypoint navigation such as gyroscope, accelerometer, compass, global positioning system receiver, and pressure sensor. A radio transmitter (MX20 Hott, Graupner, Stuttgart, Germany) with range of up to 4 km was used to remotely control the UAV.

A modified multispectral digital camera, XNiteCanon SX230 NDVI (LDC LLC, Carlstadt, NJ) with near infrared (670–750 nm) (NIR), green (G), and blue (B) bands was used for aerial imaging. The camera was mounted on a mount underneath the UAV that is capable of automatically adjusting to the nick and roll shifts during flight. Alternately, the nick and roll can be adjusted using the radio control transmitter. A firmware was used to enable geo-referenced interval shooting to acquire images every 5 s during UAV flight. The captured 8-bit JPG images with resolution of 12.1 megapixels (4000 $\times$ 3000) were stored on-board the camera card.

During preliminary evaluation, flying altitude was adjusted to acquire a multispectral camera image covering the study plots. At this time, a simple digital camera (Sony NEX-5N, Sony Electronics Inc.) was also used to estimate the spatial resolution of the two cameras at different altitudes. Sony NEX-5N is a 16.1 megapixel camera with a 4912 $\times$ 3264 image resolution. The images